Humanoids for Lunar and Planetary Surface Operations

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Abstract. This paper presents a vision of humanoid robots as human's key partners in future space exploration, in particular for construction, maintenance/repair and operation of lunar/planetary habitats, bases and settlements. It integrates this vision with the recent plans for human and robotic exploration, aligning a set of milestones for operational capability of humanoids with the schedule for the next decades and development spirals in the Project Constellation. These milestones relate to a set of incremental challenges, for the solving of which new humanoid technologies are needed. A system of systems integrative approach that would lead to readiness of cooperating humanoid crews is sketched. Robot fostering, training/education techniques to enhance and in conjunction with cognitive/sensory/motor development techniques are considered essential elements for achieving intelligent humanoids. A pilot project in this direction is outlined.

INTRODUCTION

The President's Vision for Space Exploration (The Vision) formulated in early 2004 established human and robotic space exploration as the primary goal for the U.S. Civil Space Program. Its principal goals are sustained and affordable human and robotic missions to explore and extend the human presence across the solar system. Project Constellation Spirals is the name for the phases of Human space flight system development program that implement the Vision. The exploration plan starts with human returns to Moon as a stepping stone for future missions to Mars. Spiral 1 addresses the first crewed CEV flight in LEO, by 2014, Spiral 2: the first human lunar return, by 2020, Spiral 3: the Moon as a testbed for Mars, by ~2023, Spiral 4: the deployment of launch vehicle for Mars exploration, by ~2026, Spiral 5: the development of interplanetary transportation vehicle and support infrastructure that could take humans to Mars and beyond, by ~2029, and Spiral 6: the deployment of transformational new systems for surface access and operations to enable human excursions to the surface of Mars, after 2030.

Sustained and *affordable* are the key aspects that would transform the Vision into reality. Robots will be important players in ensuring these aspects. Once humans start operating on the lunar/planetary surface an important need is to provide surface systems that support the crew for long (42-98 days) missions. This need will start as early as Spiral 3, which requires the development and deployment of additional surface systems necessary to support the crew for the long duration missions; separate cargo missions will be sent to a dedicated site prior to the crew's arrival. Surface systems will provide "basic functional capabilities including habitation, communication, power, extended range mobility, enhanced science capabilities, etc." While in Spiral 2 the vehicle that transports the crew to the lunar surface must support human exploration, in Spiral 3 the crew will transfer to a lunar habitat for the long duration stay. (page 17, ESMD, 2004).

A definition of the first long-term habitats and laboratories has not yet been formulated, and without it, although a certain level of construction assembly will likely be required, one can not exactly estimate how efficient will be the use of robots for their assembly. On the other hand, as the size and functionality of habitats/labs will grow, and true space settlements will be established on Moon and Planetary surfaces for research, exploration and exploitation, it is very likely that robots will be tools and assistants, at first, and eventually the main responsible for the assembly and maintenance of such constructions. These robots will be developed through current and successor programs of The Exploration Systems Research & Technology Programs, under the present organization using the Advanced Space Technology Program for developing the lower TRL technologies, and maturing within the Technology Maturation Program, for example under Lunar and Planetary Surface Operations Element.

What kind of robots will perform the construction/assembly and maintenance? There is a consensus within the robotic technologists on the need for intelligence and autonomy for these "construction workers". The shape, strength, flexibility are related to the tasks to be performed. Arms/manipulators are certainly needed; mobility is needed (not so much by wheels, which is efficient on transportation over distances in terrains without obstacles, but is less useful when building on ladders and scaffolds) legs being the preferred solution; eyes are needed, and two of them would provide necessary stereo vision and estimates of distances to various objects around. Without further arguments it will be stated that, for the roles related to constructing and maintaining these habitats, humanoid characteristics are no worse, if indeed not better, than other robotic shapes.

HUMANOIDS AS KEY PARTNERS FOR SURFACE OPERATIONS

Robotic systems already have a key role in space exploration. "Extension" robots, of various shapes, with sensing/motor/cognitive capabilities different than ours - extension of ours – provide increasingly invaluable service to exploration, offering advantages in sensing, communication and actuation in space or on/around planetary surfaces. On the other hand, "replacement" robots - substitutes for humans in what humans do best - would eliminate the risk of exposing astronauts to hazards of flight and operation in space in harsh environments, and certainly would be more cost effective in time. Humanoids may have the best shape for replacement robots. Certain advantages have been recognized early, including the ability to use the same tools as humans, and to best fit/operate in environments designed for humans. One should add that humanoids combine in the same platform a diverse variety of capabilities of use on the space planetary settlements: e.g. ability to climb on scaffolds and ladders, as well as to manipulate assembly modules alone or in cooperation with humans during habitat construction, to go down in a abrupt rocky crater during exploration, to carry a human in its arms in an emergency situation. These are things that no other robotic platforms currently developed can do.

Recent studies also show additional advantages of humanoids, summarized here after (Stoica, 2004): a) Human interaction with robots is easier if the robots are humanoid; b) Robot acceptance by humans is easier for humanoid shape; c) Efficiency of teaching/programming a robot is highest with humanoids. In particular related to this last aspect, one should stress here that although mobility, flexibility and adaptation to human environments offered by human shape is a convenient advantage, ***the key reason for preferring humanoids is their optimal shape for being taught by humans and learning from humans,*** **considered the only ways to develop cognitive and perceptual/motor skills for truly intelligent, cognitive robots**. A wealth of knowledge ready to be transmitted to humanoids is waiting to be used: while in the first stage robots may learn directly from humans, in the future they could learn by watching humans on training videos and movies.

Ideal for replacement or for interacting with humans, humanoids have great chance to become a key partner in space exploration. Humanoids could build habitats prior to human arrival, assist/cooperate with humans while there, perform maintenance and ensure continuity (sustained activity) exploration and exploitation of resources between astronauts' visits; they will be the first permanent colonists of planetary space stations/settlements.

The main utility of humanoids is seen in relation to long-term operations on Moon, Mars or other future planetary settlements. Thus, the appropriate beginning of insertion of humanoid technology into missions is 2023 – 2030 timeframe - in relation to Spirals 3, 5 and 6. The progressive set of needed roles and capabilities in this context can be ordered as follows (all refer to autonomous humanoids):

a) Assistants to astronauts for habitat assembly/construction tasks, circa 2028

b) Builders, robotic crews/teams building habitats without human intervention, circa 2033

c) Explorers, site selection, sub-surface sample collection, return to station, laboratory tests, circa 2040.

d) True colonists, capable to perform large scale mining operations, facilitate transportation of resources to Earth, building habitats, soil transformation, energy production, circa 2050.

The above scenario may appear as science-fiction, or the dates may appear to be too soon in the future. One should remember however, the great number of cases when a pessimistic prediction regarding the progress or extent of a technology has been proven false. On the other hand, the conquest of artificial intelligence, which is key to humanoids (not the shape), has been underestimated several times since the 1950s. The prediction for the age of humanoids has also been pushed further, while in the 1970s being predicted for 30 years later (by late Professor Ichiro Kato, the father of humanoid robotics), it is now again (despite impressive demonstration from Japanese humanoid robots in body functionality, the cognitive capabilities are still primitive) pushed another 30 years ahead (Stoica, 1997). There is little doubt that this can be achieved, should a sustained, coordinated national/international existed; unfortunately not only does not such an effort exist, but even the benefits, efficiency or even utility of humanoids are doubted by many, outside and inside the robotics community. Certainly if one does not believe an idea, and nothing is done in that direction, its progress is unlikely. On the positive side, specific technologies that would be integrated in a humanoid as a system-of-systems are developed under various efforts – machine vision is one of the examples. A humanoid project may leverage on multiple technologies developed elsewhere, and a strong system integration effort may be able to produce a substantial advancement in capability.

Japanese humanoids proving human resemblance in shape, size, and basic mobility already exists. These robots can walk alone, go on stairs, and can be tele-operated to handle various objects. However, the mechanical aspects of these robots are more advanced than their processing capabilities – while they can give the visual appearance of human shape and motion, their cognitive capabilities are practically absent. Through an integrated effort the results of other research worldwide could be integrated to the humanoid body to provide a powerful platform to develop it to operational levels. Examples of several technologies available, yet not incorporated in humanoids include: <u>language technologies,</u> including voice recognition, speech to text and voice synthesis, which are sufficiently developed to allow simple interaction with the robot in spoken English (simple Japanese exists in some research robots); f<u>ace/gesture recognition,</u> sufficiently developed to allow robots to read "moods" of instructor, follow cues, etc (as prototyped e.g. on some MIT robots); <u>knowledge base, dialog and logical reasoning</u>, as illustrated e.g. by Cyc, proving useful artificial intelligence; <u>improved vision, hearing, olfaction, tactile, and other sensing,</u> developed to a certain extent and incorporated in various commercial devices (artificial retinas, e-nose, e-tongue). Some of the capabilities/technologies still needed include efficient and human-friendly means to transfer cognitive and motor skills to robots, cognition and self-awareness, perception from big sensory arrays (e.g. skin) and an integrated platform that combines available technologies.

FOSTERING AND TEACHING: KEY CHARACTERISTICS IN HUMANOID COGNITIVE/MOTOR DEVELOPMENT

Incorporating available technologies and developing new ones on the same integrated platform is an efficient way to bridge the gap between current state of the art and future humanoids. There is a tight connection between achieving human-friendly means for cognitive/motor skill transfer and interaction through dialog in natural language; similarly, cognition and self-awareness are also related to development of perceptual maps and schemes; embodiment and experimenting the world are dependent on perceiving the world with multiple sensors, etc. We propose to follow this path, in a developmental approach to provide the robot with cognitive/motor capabilities.

A key distinguishing characteristic of our approach at JPL is the emphasis on fostering/teaching/education (some aspects being illustrated in Figure 1). Our key beliefs for a successful path to humanoids are:

a. <u>**The essence of endowing robots with intelligence is development, not programming.**</u> Development allows building of perceptions, schema, representations, and behaviors directly through interaction with the real world environment (a set of innate/pre-programmed capabilities is assumed). This is a gradual building process, using previously learned categories. It allows the developer to better understand limitations of the operation and to design lessons.

b. <u>**The key to development is robot fostering/teaching, and not robot learning**</u>. It may be not the human capability to learn, but to teach, that contributed greatly to our progress. While we will pay great attention to learning algorithms for the robot, and incorporate the best learning techniques available, in various flavors of unsupervised, reinforcement and supervised mode, our approach emphasizes the importance of fostering/teaching techniques[1], largely overlooked by other approaches yet considered key to development of cognitive/motor skills. As examples, human imitation of the robot in its initial actions (before the robot itself starts to imitate), providing experiments/lessons of increasing difficulty and helping the robot ("keeping it by the hand") while learning. [2]

c. **<u>The main techniques for fostering/teaching by a human or robot are imitation, explanation, and demonstration.</u>** The robot needs help during learning. In initial phase human imitation of robot movements provides the robot with feedback. Later its own imitation of the human helps acquiring new behaviors. Explanation is paramount for guidance and for understanding the movements/tasks/behaviors. Demonstration provides a solution on how to solve a problem. Direct help from the human, in the form of supporting the robot during its first steps, providing a helping hand in need, positioning it by hand, etc., all are a great help to the robot. Interactive teaching is extremely important since it adapts to context.

d. **<u>Robot's ability to teach is the proof of learning</u>.** The ability to teach is a validation that the essence of the task is grasped, that it is generalized and can be applied in a different context, that it is "conscious", meaning it has a flexible representation in context of self and outside world, and a rationale for why it is that way. With humans it is also common to say that professors really learn a subject only when/after they teach it.

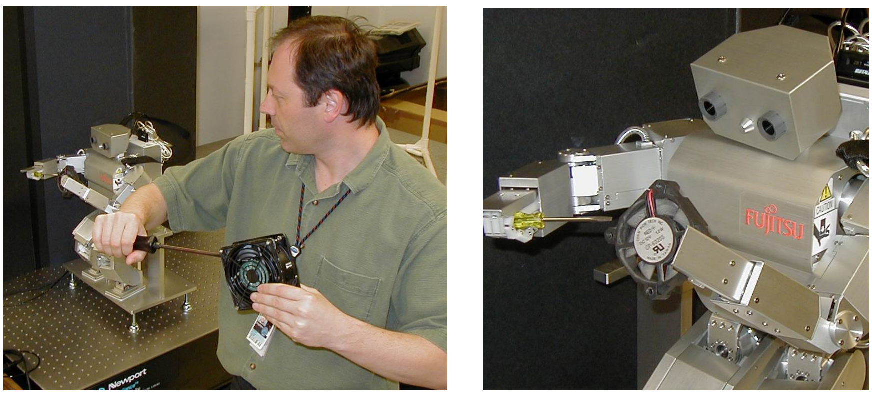

FIGURE 1. Human imitating the robot, before the robots imitates human. Pictures with a HOAP-2 robot.

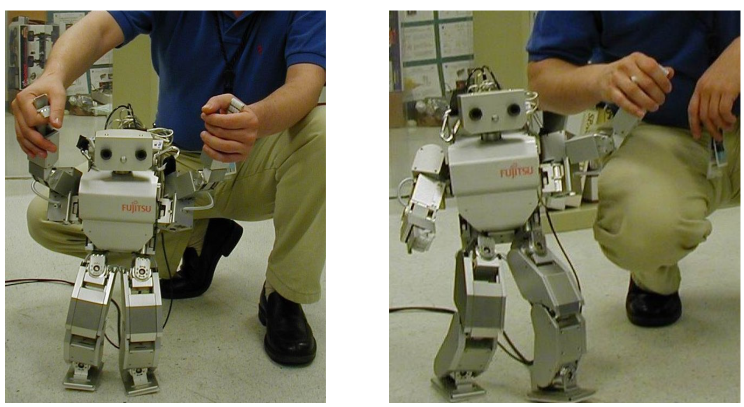

FIGURE 2. Teaching the robot walk, later providing only "a helping hand". Pictures with a HOAP-2 robot.

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[1] In the animal world fostering is considered an important component to ensure survival of the species. Interestingly, it is been observed that the more "advanced" a species is, the longer the period of immaturity of its offspring — in other words the longer the parents need to foster their children. It is this period when the young ones develop the skills that would make them successful in life.

[2] The parents act as first teachers taking the young ones through various phases of learning. In time the grown-up will in turn teach others (not seldom themselves learning more during/through teaching)

Our previous work demonstrates the capability of transferring motor skills to anthropomorphic robots through vision-based imitation. After initially the humans imitated the robot arm movements flailing at random at first, the robot watching the human developed an association between its motor commands and visual inputs as reactions to its moves. Reversely, it later commanded its arm to positions associated to arm movements of instructor, imitating and learning from its moves. Experiments with two robots imitating and learning from each other were also demonstrated (Stoica, 1995), (Stoica, 1999), (Stoica, 2001).

A PILOT PROJECT FOR HUMANOID DEVELOPMENT

A preliminary study phase for a pilot project to develop a humanoid robot able to construct/assemble habitats and operate in human environments is currently under way at JPL.

The initial experimental platform is a 50cm tall Humanoid Open Architecture Platform Second generation (HOAP-2) Fujitsu robot. The robot operates autonomously under controls from its own computer, or can be wirelessly controlled from a command environment under real-time Linux. The vision system consists of two CCD cameras, capable of capturing frames of 640 by 480 pixels. The body motions are provided through 25 servo actuators: 6 for each leg, 4 for each arm, 1 for each hand, 2 for the head, and 1 for its waist. There are 4 pressure sensors on the bottom of each foot, and an accelerometer and gyroscope inside the torso. Additional pressure sensors were mounted on the body, to enhance tactile sensing, for detecting potential obstacles, balancing a carrying load, etc.

Initial experiments included development of simple vision-guided operation and adaptive walking schemes. The vision uses conventional techniques for image processing to isolate simple color-marked objects, estimate distance to the them, and take several actions including walking towards them, grabbing, carrying and releasing the objects (Xu, 2004). Walking, first without a load and then with a load - carrying an object that it picked from the environment, was implemented using Zero Moment Point (ZMP) walking, with the center of gravity maintained over the robot's support structure at all times (Figure 3). A parametric walking scheme was used, with parameters defining the size of each step, the height of each step, the angle the robot turns per step, and the position of the feet when the robot is standing; these parameters are adjustable, and were used to adapt to changes caused when the robot grabbed and carried a load; these are to be further used for adaptation to optimal values for various environment/context conditions (Jeanne, 2004).

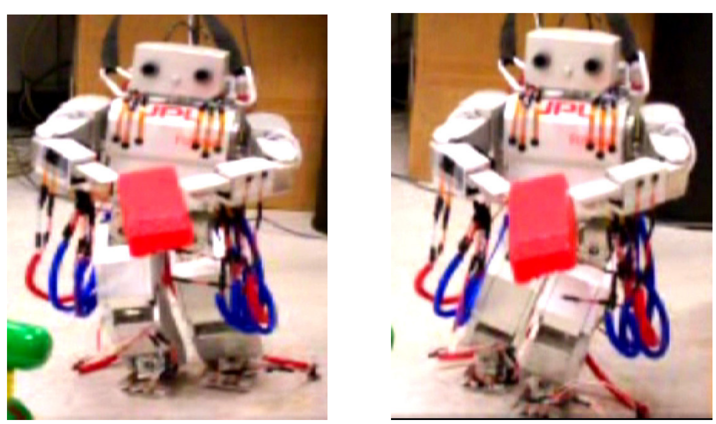

FIGURE 3. HOAP has autonomously located, picked and is walking with a load.

These experiments illustrated basic capability of the robot to visually locate, approach, fetch, handle, transport and release simple loads. The next 9-month phase will target the assembly of a cubic frame from tubes of length of ~60cm, longer than the height of the robot. The tubes will be stacked in an arbitrary region of the workspace; the robot will assemble the structure at a different marked point. The tubes will have a simple latching mechanism. The robot will have to pick up a new bar, approach the assembly structure, position the bar/structure in appropriate relative position and bring them together for the latch (Figure 4).

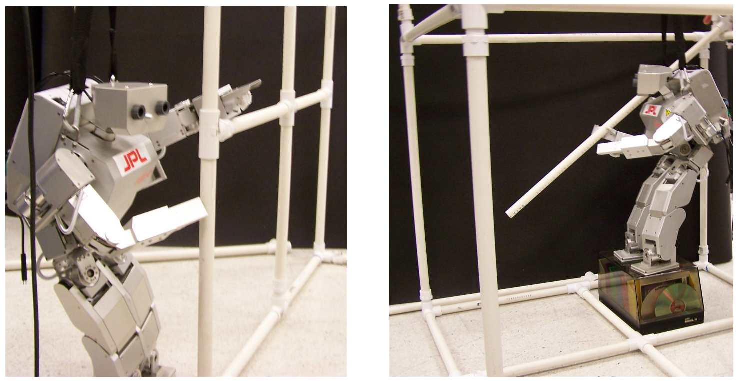

FIGURE 4 Future target capability in assembly of a frame, pictures for visualization of the concept.

In the next four years the proposed pilot project is an effort toward a demonstration of a full–scale humanoid that can walk inside/outside buildings, transport objects and assemble modular components (select/lift/transport/place in right position). It is intended to use a human-size humanoid body obtained either from SARCOS or from a Japanese vendor. The capability is practically within reach by integration of two SARCOS platforms, a full-body humanoid, legged, but anchored/not walking) and a SARCOS legged exoskeleton developed for DARPA which can walk; additional sensors would be added. Important planned milestones are: Year 1, demonstration of vision-guided walking indoors, on a flat surface, and avoiding interfering obstacles. Year 2, demonstration of handling and positioning a variety of objects using vision. The humanoid would learn primitive cognitive and motor skills. Year 3, the demonstration of humanoid robot autonomously navigating/handling objects, climbing a ladder. Year 4, demonstration of simple construction/assembly tasks, carrying objects, position them in desired locations, moving on stairs and carrying a tool while climbing a ladder.

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